Alaska Sablefish Model Update

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Introduction

This preliminary assessment document attempts to address some recent comments and recommendations made by reviewers of the Alaska sablefish assessment including the Center for Independent Experts (CIE), the Joint Groundfish Plan Team (JGPT) of the North Pacific Fishery Management Council (NPFMC), and the Science and Statistical Committee (SSC) of the NPFMC. In this document we focus primarily on alternative modeling approaches for fishery selectivity and developing a more informative prior on natural mortality. Both of these analyses were done in response to the primary criticism of the 2016 CIE review that the sablefish assessment model provides "unrealistically precise estimates of absolute stock size and should better account for uncertainties relating to natural mortality rate…" and other fixed quantities (Carruthers 2016 CIE Report).

Fishery selectivity

The sablefish assessment model moved from a single-sex model to a split-sex model in 2006 (Hanselman et al. 2006). Because the sablefish assessment estimates selectivity at age (not length), this doubled the number of selectivity parameters which led to some difficulty in estimating all of the parameters simultaneously. Also in 2006, the Gulf of Alaska (GOA) trawl survey was included for the first time as a recruitment index which added two more selectivity curves. The trawl fishery was previously estimated with the exponential-logistic curve to allow it to be dome-shaped. This three parameter functional form that can become unstable when the parameters are highly correlated. In 2008, a number of simplifications were implemented to the selectivity functions with the objective of addressing model instability and high selectivity parameter CVs and correlations (Hanselman et al. 2008). In that assessment, the exponential-logistic selectivity function was replaced by the two parameter gamma function for the trawl fishery and a one parameter power function for the GOA trawl survey. Several of the selectivity shape parameters were linked (the males and females used the same shape parameter) for the fixed gear logistic curves. These changes resulted in higher parameter precision and lower parameter correlations, a more stable model, and a reduction of 13 parameters.

A decade later, some of the fits to the compositional data have degraded. This could be due to changes in spatial patterns in the fishery and unusual recruitment events. In the meantime, 10 more years of data may now allow for better estimation of additional selectivity parameters. This has led to several accumulated recommendations from the Plan Teams, SSC, and 2016 CIE review regarding selectivity that this preliminary assessment will attempt to address. These comments include:

1) "The SSC also suggests that the next assessment include further investigation of the lack of fit to the plus group in recent fishery age compositions, and development of a prior for natural mortality." – December 2017
2) "The Teams recommended that further evaluations of selectivity options be pursued." – November 2017
3) "Aggregated summary observed versus expected age compositions by fleet and survey from the model are acceptable, but do indicate that there is room for further improvement through

selection of alternative selectivity functional shapes or adjustment of the value of fixed or number of estimated selectivity parameters." – Klaer, 2016 CIE review

Two studies on sablefish (Jones and Cox 2018, Maloney and Sigler 2008) and one on Pacific halibut (Clark and Kaimmer 2011) have used mark-recapture data to suggest that their respective longline fisheries have some degree of dome-shaped selectivity. Jones and Cox (2018) showed that the dome-shaped gamma distribution provided the best fit to tagging data from British Columbia (Figure 1). It should be noted that they were fitting selectivity-at-length models, so the shape may not translate, but evidence of dome-shapedness would. Maloney and Sigler (2008) used tagging data from known-age sablefish to suggest that a dome-shaped exponential-logistic function provided the best fit to the longline fishery recaptures (Figure 2) for selectivity at age. Finally, Clark and Kaimmer (2006) showed for halibut, that while a gear may be asymptotic within an area, the spatial distribution of the fishery may result in a dome-shaped selectivity curve for the longline fishery based on where the fishery operates relative to the overall population (Figure 3). These studies and requests by review bodies are the rationale for re-examining sablefish fixed-gear fishery selectivities.

Natural mortality

Natural mortality has been modeled in a variety of ways in previous Alaska sablefish assessments, and in other management areas (British Columbia and U.S. West Coast). For Alaska sablefish assessments before 1999, natural mortality was assumed equal to 0.10. For assessments from 1999 to 2003, natural mortality was estimated rather than assumed equal to 0.10; the estimated value was about 0.10. For the 2004 assessment, a more detailed analysis of the posterior probability showed that natural mortality was not well-estimated by the available data. The posterior distribution of natural mortality was very wide, ranging to near zero. Parameter estimates even for MCMC chains thinned to every 1000_{th} value showed some serial correlation. For the 2005 assessment we assumed that we knew the approximate value of natural mortality very precisely (CV of 0.1% for prior probability distribution) and that the approximate value was 0.10. At this level of prior precision, it was essentially a fixed parameter. Using such a precise prior for a parameter that we do not think is estimable serves no purpose except to acknowledge that we do not know the parameter value exactly. It was pointed out during review that estimating M this way was misleading and an improper use of Bayesian priors, so in 2006 we returned to fixing the parameter at 0.10. However, in 2016, in response to the 2016 CIE review, we once again estimated natural mortality, this time with a less precise prior (CV = 10%) resulting in an estimate that deviated from 0.10, but not greatly (M = 0.097 in 2017). Nonetheless, it was still a wholly *ad hoc* estimate of prior precision. In this document, we attempt to develop a more informed prior based on life history methods and a mark-recapture estimate from the movement model of Hanselman et al. (2015).

Methods

Fishery selectivity

We present a number of scenarios to explore whether there are time-invariant or time-variant selectivity alternatives that produce a substantively better fit to the data while still considering model parsimony. The base model 16.5 from the 2017 assessment (Hanselman et al. 2017) should be the standard of comparison. However, because the shape parameters of the logistic curves for male and female selectivities were shared in Model 16.5, we had to estimate these two parameters so subsequent models could be compared on common ground. Thus, a very similar model (16.5a) is the standard of comparison for the models. We evaluated three groups of alternative models:

1) Time-invariant selectivities for the IFQ fixed gear fishery (1995 – 2017),
2) Time-variant selectivities for the IFQ fixed gear fishery (1995 – 2017),
3) Time-variant selectivities for all fixed gear catch (1960 – 2017).

A fourth group exploring more complex time-invariant selectivities for the GOA trawl survey (1984 - 2017) was attempted but we found that there were serious estimability and convergence issues, so we narrowed the focus to fixed-gear fishery selectivity only.

We examined parametric and non-parametric selectivity forms (Table 1). The parametric selectivities that we compared were the logistic, exponential-logistic, and gamma functions (Hanselman et al. 2017). For the time-varying parametric selectivity models we only use the logistic and gamma function where the $a_{50\%}$ (age at 50% selectivity for the logistic) and $a_{100\%}$ (the peak of the gamma function) parameters, respectively, are allowed to vary each year.

The non-parametric selectivities used are similar to those used for fishery selectivity in the EBS pollock model (Ianelli et al. 2017). Non-parametric selectivity means estimating an additional parameter for each age, and in time-varying methods up to one additional parameter for each age every year. For all of the nonparametric selectivity models, ages after 15 are set to be equal. Sablefish by this age are fully mature and fully grown (>95% mature and L_{inf}), and would be expected to behave similarly, and have similar availability to the gear. Selectivity at age is forced to have a mean value of one within a year and are constrained by penalties of analyst specified magnitudes to prevent large changes between ages and extreme dome-shaped behavior. The full suite of different selectivity options explored in this analysis paper can be found in Table 1.

Natural Mortality

Natural mortality (*M*) is notoriously difficult to estimate, but a number of life-history correlates have been used to approximate its value. An online tool[1] has been developed that compiles the primary life-history based estimators and weights them by groups of input data. The life-history parameters used to populate the tool are shown in Table 2. Since multiple estimators may use the same life history data, the results were divided by the number of related estimators. For example, there were four estimators based on maximum age, so they were each weighted by 0.25 in the composite value. The tool then compiles all the estimates to make a composite prior density using the empirical cumulative distribution (ECD) of the point estimates. We use this tool here as a first step to a more informative prior. The results of the estimates are shown in Table 3. Several of the estimators produced very low (sometimes negative) and very high estimates so we omitted the highest two (Jensen LVB estimators) and the lowest two (Alverson and Carney; Chen and Watanabe). The mean and coefficient of variation (CV) of the ECD were 0.187 and 0.429, respectively (Table 3). The references behind these various life-history estimators are shown in Table 4.

The second step is combining the composite density with an estimate of *M* from the sablefish tag-recapture data set which was used to estimate movement rates from 1979 – 2011 (Hanselman et al. 2015). For the purpose of this analysis, we used this movement model with no size delineations (i.e., all tag-release-recovery data) and instead of fixing *M* as in the original study, it is estimated (with no prior). The estimate from this model was 0.0852 with a Hessian derived CV of 0.0183. The prior for the assessment model was then derived by sampling from the tool-based and movement model-based distributions and combining them with equal weighting. The lognormal mean and CV of this distribution then becomes the

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[1] Natural mortality estimators in The Barefoot Ecologist's Toolbox: http://barefootecologist.com.au/shiny_m

prior to be tested in the assessment model which has an arithmetic mean of 0.116 and CV of 0.208 (Figure 4).

We compared assessment models with different priors for natural mortality to the model used for the 2017 assessment (16.5). Model 16.5 used a prior distribution with a mean of 0.10 and a CV of 10%. Model 16.5r used the new prior developed in this analysis. In addition, results were compared with a model with natural mortality fixed at the new prior mean (16.5s), and a model with the new prior mean and a non-informative prior (16.5t) (Table 5).

Results

Fishery selectivity

While we looked at many models, we only included those that had a maximum gradient <0.001 and those that had a positive definite Hessian. We compared the models across a number of criteria, including fit to the data ('data -lnL'), number of parameters, improvement of fit to the plus group, retrospective statistics as recommended in Hanselman et al. (2013) including the typical 'Mohn's rho', and tradeoffs between fits to individual important data sets (survey and fishery age composition, fishery length composition, and longline survey index fit). The models range in complexity, with the most complex estimating over 1,000 parameters (Models 16.5n, 16.o). However, these parameters are constrained random walks so their effective number of parameters is probably considerably less. One advantage of the last group of models (Models 16.5n – 16.5z) is that while they have more parameters, they make less rigid assumptions about what time blocks to fit for selectivity throughout the history of the fixed gear fleet (e.g., foreign, derby, and IFQ), and instead allow the selectivity to change over time as informed by the data. Models discussed below will focus primarily on models that show an improvement in the overall fit to the data compared to Model 16.5a.

The time invariant models for fixed gear selectivity from 1995 – 2017 had a range of improvements or degradations of fits to the data as shown by the delta-lnL (the change in likelihood of the data components from 16.5a, Table 6). Only two of the models (16.5c and 16.5d) showed an improvement over 16.5a (delta-lnL of -8 and -11, respectively). These models used the exponential-logistic function and a minimally constrained non-parametric selectivity at age as compared to the logistic function used in 16.5a. Model 16.5c did not improve the fit to the fishery age data, but did improve the fit to the survey age data, and worsened the fit to the plus group. Model 16.5c has poor retrospective performance (Table 7), primarily due to lack of convergence in some years because of instability of the exponential-logistic function. Model 16.5d showed a better fit to the fishery ages, a slight improvement to the plus group, and better retrospective performance in all categories than Model 16.5a, with only a slight degradation in fit to the survey ages. The selectivity shape seems quite reasonable for females (Figure 5), and still plausible for males.

The time-varying models mostly showed an improvement in fit to Model 16.5a (Table 6). These improvements came at a cost of adding between 18 and 878 parameters (Table 6). Two models that did not show an improved fit (16.5l and 16.5o) were those that put a high constraint on allowing selectivity at older ages to be dome-shaped, indicating that some dome-shapedness is important in describing fixed gear fishery selectivity. The two time-varying parametric selectivity models (16.5i and 16.5j) showed a small improvement in overall fit to the data (delta-lnL). Model 16.5i (logistic selectivity) improved the fit to the fishery ages, but had a minimal improvement in fit to the plus group. The time-varying selectivity

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curves seem plausible (Figures 6 and 7). Model 16.5j (gamma selectivity) showed a large improvement in the fit to the fishery ages, but somewhat at the expense of fitting the fishery size data. This model also gave the greatest improvement of fit to the plus age group. This is likely a result of the extreme-dome shapedness (Figure 8) and the large increase in M that only occurred when the gamma model was used (Table 1). The retrospective performance of Model 16.5i was similar to Model 16.5a, while Model 16.5j was poor.

Of the time-varying models that improved the fit to the data, the best fitting model is the very lightly constrained Model 16.5n, which estimates annual parameters at age for every year since 1960 (npar = 1111, Table 6). The –lnL for the fit to the fishery age composition decreases by about 50% and it has the next best fit to the plus group from Model 16.5j. While the increased flexibility of estimating so many parameters results in a good fit to the data, the shape and annual variability of the resulting selectivity curves may be implausible (Figures 9 and 10). Recognizing this, several models were presented with time blocks and higher constraints that seemed to show an improvement relative to Model 16.5a in terms of fit and produced more plausible selectivity patterns than Model 16.5n (e.g., Model 16.5z, Figures 11 and 12). Model 16.5z is a model with 2-year time blocks that also uses the natural mortality prior developed in this document. The effect of that less precise prior can be observed as it produces the lowest value of M and has the 3rd best fit to the plus group. However, other than perhaps Model 16.n, all of the time-varying models for the full time series of fishery selectivity produce undesirable retrospective performance, particularly in recent years (high values of Phi, Table 7). Qualitatively, it is interesting that the time-varying selectivities all show a markedly different pattern starting in about 2013 with lower selectivity of younger fish. This is similar to the pattern shown in Hanselman et al. (2017) where the fishery has recently caught a lower proportion of fish than expected relative to the survey age compositions.

Natural Mortality

The assessment model with the new prior for natural mortality (16.5r) was compared to the 2017 assessment (16.5), a model with natural mortality fixed at the prior mean (16.5s), and a model with the new prior mean and a non-informative prior (16.5t) (Table 5). The new prior had a minor influence on the point estimate of natural mortality, but actually resulted in a slightly degraded fit. This may indicate that the age data in the sablefish assessment has informative data on natural mortality, and that information is more consistent with the mark-recapture estimate of M. In fact, the posterior distribution of natural mortality estimated by MCMC from Model 16.5r is very precise relative to the prior distribution (Figure 13).

Fixing the estimate of M at the point estimate of the prior had a more substantial effect on the model results and fits, with a slight decrease in model fit ('data –lnL'), and a relatively large increase in total biomass (+27%). Finally, estimating natural mortality essentially freely (CV = 10, Model 16.5t), results in a minor improvement in fit to the data. All methods that estimate M produced very similar values. Incidentally, the estimates of *M* produced by all of the different selectivity model runs were relatively robust to the choice of fishery selectivity (Table 1) as well.

Discussion

Fishery selectivity

The exploration of new time-invariant selectivity curves showed some potential for modest improvement in the fit to recent fishery age compositions. Whether these modest improvements are worth adopting a new model is unclear. However, it is likely worth considering adopting Model 16.5a, where it appears that the previously linked selectivity parameters can now be well-estimated and improves the (already small)

retrospective patterns in Model 16.5. None of these models made significant progress towards improving the fit to the plus group of the fishery age data. Model 16.5d is also worthy of consideration, but is not a dramatic improvement and adds additional complexity. The shape of female selectivity in Figure 5 for Model 16.5d is similar to the selectivity shapes authors of past sablefish assessments and sablefish assessments in other regions have proposed (Figures 1 – 3).

The time-varying alternatives in general performed well in terms of the fits to the data, but this came at the cost of adding many more parameters. Some of the models shown, and many that were not shown, resulted in selectivity shapes that seemed implausible. The models that fit time-varying selectivity for all years were intuitively pleasing because they unified the estimation of selectivity for the fixed gear fisheries under the same assumption throughout the history of the fishery. Model 16.5z seemed to help balance model fit without adding the full number of potential parameters by using 2-year time blocks. However, the retrospective performance of all of the time-varying selectivity models that fit the data better than Model 16.5a, with the exception of the time-varying logistic model, was poor. Beyond consideration of parsimony alone, this should suggest caution before introducing these high-parameter models. Despite recent suggestions that time-varying selectivity should be best practice (Martell and Stewart 2013) and claims that retrospective patterns can be alleviated (Szuwalski et al. 2017), these results specific to sablefish suggest otherwise. The Plan Team Retrospective Investigations Group (Hanselman et al. 2013) also showed that models with a high number of parameters tended to be more likely to exhibit poor retrospective performance. One additional uncertainty that exists when adopting one of these time-varying methods is determining what selectivity curve should be used for projecting ABCs and OFLs in the following years, given that the estimates are highly dependent on fishery age data that only exist up to one year prior to the current model year. This is often chosen to be a short or long term average. An additional tactic that we explored was using the estimate of selectivity from a year where the numbers-at-age most closely matches the projected numbers-at-age.

In conclusion, there is evidence from other studies and the analyses shown here that there is likely at least some dome-shapedness in the fixed gear selectivity curve. The time-varying explorations do indicate that in recent years there does appear to be some different patterns in selectivity than historically. However, at this time, the inclusion of time-varying selectivity may be premature and of minimal benefit to the overall performance of the sablefish stock assessment. For the 2018 sablefish assessment, we may attempt to include an alternative similar to Model 16.5d.

Natural Mortality

The previously used prior mean for natural mortality for sablefish was based on estimates from older literature and past practice. The variance of that prior was *ad hoc* based on the senior author's judgment. The prior developed in this paper is more rigorous and includes a number of peer-reviewed methods, as well as an estimate from our large independent tag-recapture database for sablefish. Other ways of weighting the various estimates of M for the prior could have been employed, but it is clear that the natural mortality prior should be more uncertain than the current prior. The effect on the stock assessment of inclusion of this prior is negligible, as the model estimate of natural mortality is becoming well informed as more and more age data accumulate. The estimation of M alone was not helpful in resolving the poor fit to the fishery age plus group in some years.

In conclusion, we recommend the inclusion of this prior in the 2018 assessment. While it may have a low impact on the results, it was a useful exercise to explore the various life history methods and the tagging data to show the wide-range of possible values that natural mortality could be. These results should also provide comfort that the previous and current estimates of natural mortality were reasonable approximations.

References

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Table 1. Models with different forms of selectivity and associated natural mortality values.

Model #	Selectivity form	Time-varying	Years	Blocks	Const-rained	Smooth Penalty	Dome-shaped Penalty	M
16.5	Logistic	No	1995-2017	--	No	--	--	0.098
16.5a	Logistic	No	1995-2017	--	No	--	--	0.097
16.5b	Gamma	No	1995-2017	--	No	--	--	0.138
16.5c	Exponential-logistic	No	1995-2017	--	No	--	--	0.086
16.5d	Coefficients	No	1995-2017	--	No	1	1	0.097
16.5e	Coefficients	No	1995-2017	--	Yes	10	10	0.095
16.5f	Coefficients	No	1995-2017	--	Yes	50	10	0.091
16.5g	Coefficients	No	1995-2017	--	Yes	10	50	0.090
16.5h	Coefficients	No	1995-2017	--	Yes	50	50	0.094
16.5i	Logistic	Yes	1995-2017	Annual	No	--	--	0.097
16.5j	Gamma	Yes	1995-2017	Annual	No	--	--	0.136
16.5k	Coefficients	Yes	1995-2017	Annual	Yes	10	10	0.088
16.5l	Coefficients	Yes	1995-2017	Annual	Yes	50	50	0.096
16.5m	Coefficients	Yes	1995-2017	Annual	Yes	1	1	0.086
16.5n	Coefficients	Yes	1960-2017	Annual	Yes	1	1	0.078
16.5o	Coefficients	Yes	1960-2017	Annual	Yes	20	100	0.089
16.5p	Coefficients	Yes	1960-2017	5 year	Yes	3	10	0.083
16.5q	Coefficients	Yes	1960-2017	2-year	Yes	5	5	0.080
16.5z	Coefficients	Yes	1960-2017	2-year	Yes	3	3	0.073

Table 2. Parameters used in the Barefoot Ecologist natural mortality tool (http://barefootecologist.com.au/shiny_m) for developing a sablefish natural mortality prior. Values are the mean of the male and female parameters.

Life history parameter	Value
Maximum age (years):	84
VBGF Growth coeff. k_l:	0.255
Age at maturity (years)	6.5
VBGF Growth coeff. wt. (k_w, in g):	0.255
Linf (in cm):	74.0
VBGF age at size 0 (t_0)	-2.11
Asym. weight (Winf, in g):	4.32
Water temperature (in C):	6

Table 3. Estimates of natural mortality from the life history based estimators and their respective weights in the composite posterior. Tag-recapture (highlighted yellow) is integrated directly with the posterior of the rest of the weighted estimates. The top two and bottom two estimators were given zero weight (greyed out cells). References for each estimator are given in Table 4.

Method	M	Weight
Then_Amax 1	0.0844	0.25
Then_Amax 2	0.0608	0.25
Then_Amax 3	0.0634	0.25
Hamel_Amax	0.0643	0.25
AnC	0.0000	0
Then_VBGF	0.1713	1
Jensen_VBGF 1	0.3825	0
Jensen_VBGF 2	0.4080	0
Pauly_lt	0.2780	0.5
Chen-Wat	-0.0156	0
Roff	0.1800	0.333
Jensen_Amat	0.2538	0.333
Ri_Ef_Amat	0.2350	0.333
Pauly_wt	0.3080	0.5
GSI	0.2820	1
Tag-Recapture	0.0852	CV = 0.0183
Overall	**0.1163**	**CV = 0.208**

Table 4. References for natural mortality estimators used in Table 3.

Then_Amax 1, Then_Amax 2, Then_Amax 3, Then_VBGF	Then, A.Y., J.M. Hoenig, N.G. Hall, D.A. Hewitt. 2015. Evaluating the predictive performance of empirical estimators of natural mortality rate using information on over 200 fish species. ICES J. of Mar. Sci. 72(1); 82-92.
Hamel_Amax	Hamel, O.S., 2014. A method for calculating a meta-analytical prior for the natural mortality rate using multiple life history correlates. ICES Journal of Marine Science, 72(1), pp.62-69.
AnC	Alverson, D. L. and M. J. Carney. 1975. A graphic review of the growth and decay of population cohorts. J. Cons. Int. Explor. Mer 36: 133-143.
Jensen_VBGF1, Jensen_VBGF 2, Jensen_Amat	Jensen, A.L. 1996. Beverton and Holt life history invariants result from optimal trade-off of reproduction and survival. Can. J. Fish. Aquat. Sci. 53: 820-822. Jensen, A.L. 1997. Origin of the relation between K and Linf and synthesis of relations among life history parameters. Can. J. Fish. Aquat. Sci. 54: 987-989.
Roff	Roff, D. A. 1984. The evolution of life history parameters in teleosts. Can. J. Fish. Aquat. Sci. 41: 989-1000.
Ri_Ef_Amat	Rikhter, V.A., Efanov, V.N., 1976. On one of the approaches to estimation of natural mortality of fish populations. ICNAF Res. Doc. 79/VI/8, 12.
Pauly_lt,Pauly_wt	Pauly, D. 1980. On the interrelationships between natural mortality, growth parameters, and mean environmental temperature in 175 fish stocks. J. Cons. Int. Explor. Mer: 175-192.
Chen-Wat	Chen, S. and S. Watanabe. 1989. Age Dependence of Natural Mortality Coefficient in Fish Population Dynamics. Nippn Suisan Gakkaishi 55(2): 205-208.
GSI	Gunderson, D. R. and P. H. Dygert. 1988. Reproductive effort as a predictor of natural mortality rate. J. Cons. Int. Explor. Mer 44: 200-209.
Tag-Recapture	Hanselman, D.H., Heifetz, J., Echave, K.B. and Dressel, S.C., 2015. Move it or lose it: movement and mortality of sablefish tagged in Alaska. Canadian journal of fisheries and aquatic sciences, 72(2), pp.238-251.

Table 5. Assessment models with different priors for natural mortality with the prior mean and CV on the arithmetic scale shown. Log likelihood values overall ('-lnL'), total for the data ('Data-lnL'), and important subcomponents across selectivity models. 'delta-lnL' is the reduction in -lnL from Model 16.5.

Model #	M estimation (mean, CV)	-lnL	Data -lnL	delta-lnL	# Pars	M
16.5	0.1, 0.1	1575.64	1536.76	--	231	**0.098**
16.5r	0.116	1577.96	1540.16	3.4	230	**0.116**
16.5s	0.116, 0.206	1575.93	1537.04	0.28	231	**0.100**
16.5t	0.116, 10	1575.65	1535.37	-1.39	231	**0.102**

Table 6. Log likelihood values overall ('-lnL'), total for the data ('Data-lnL'), and important subcomponents across selectivity models. 'delta-lnL' is the reduction in -lnL from Model 16.5a, '-lnL/par' is the reduction in -lnL per additional parameter from Model 16.5a, 'PlusGroup' is the sum of the squared residuals of the plus group fit (age 31), and '% of base' is the percent of the sum of squares relative to Model 16.5a.

Model #	-lnL	Data-lnL	delta -lnL	Param eters	-lnL/par	Fishery Ages	Surv Ages	Fish Size	LL Surv Index	Plus Group	% of base
16.5	1576	1537		231	--	239	219	41	30	0.032	100%
16.5a	1559	1521	0	233	--	240	207	40	29	0.032	100%
16.5b	1610	1558	38	233	--	262	207	63	26	0.033	102%
16.5c	1555	1513	-8	235	-3.87	236	201	38	29	0.033	102%
16.5d	1554	1509	-11	258	-0.46	211	226	35	29	0.032	98%
16.5e	1579	1535	14	258	0.56	223	222	36	29	0.032	98%
16.5f	1617	1572	51	258	2.05	239	221	36	29	0.032	98%
16.5g	1587	1547	26	258	1.06	233	218	38	29	0.032	99%
16.5h	1628	1584	63	258	2.52	251	220	38	29	0.032	100%
16.5i	1541	1501	-19	276	-0.45	207	218	42	30	0.032	98%
16.5j	1561	1506	-14	276	-0.33	182	218	62	27	0.020	60%
16.5k	1517	1474	-47	603	-0.13	162	202	35	28	0.025	76%
16.5l	1599	1548	27	603	0.07	209	207	39	28	0.027	85%
16.5m	1460	1416	-105	603	-0.28	125	199	33	27	0.023	71%
16.5n	1430	1385	-136	1111	-0.15	118	173	31	15	0.022	68%
16.5o	1580	1536	16	1111	0.02	201	198	41	30	0.027	85%
16.5p	1515	1472	-49	436	-0.24	168	197	36	27	0.026	80%
16.5q	1500	1456	-65	691	-0.14	155	191	33	27	0.028	87%
16.5z	1481	1435	-86	691	-0.19	142	185	33	26	0.022	69%

Table 7. Retrospective statistics for female spawning biomass across models with different selectivities. Mohn's ρ is the measure of bias in the estimates in the last 10 years, Wood's hole ρ is the bias in full the time series, RMSE is the root mean squared error of the spawning biomass over all years, and φ is the ratio of recent (Mohn's ρ) to historic (Wood's hole ρ) which indicates whether retrospective bias is higher recently rather than overall.

Model #	Mohn's ρ	Wood's Hole ρ	RMSE	φ
16.5	0.068	0.063	0.412	1.079
16.5a	0.047	0.066	0.427	0.712
16.5b	0.228	-0.245	2.016	-0.931
16.5c	0.598	0.446	1.318	1.341
16.5d	0.006	-0.006	0.186	-1.000
16.5e	0.054	-0.007	0.460	-7.714
16.5f	0.055	-0.009	0.423	-6.111
16.5g	0.136	0.181	0.692	0.751
16.5h	0.025	-0.041	0.472	-0.610
16.5i	0.105	0.104	0.411	1.010
16.5j	0.282	-0.160	1.379	-1.762
16.5k	0.213	0.142	0.505	1.500
16.5l	0.063	-0.045	0.496	-1.400
16.5m	0.274	0.195	0.611	1.405
16.5n	0.160	0.091	0.367	1.758
16.5o	0.226	0.124	0.434	1.823
16.5p	0.191	0.157	0.522	1.217
16.5q	0.228	0.159	0.544	1.434
16.5z	0.244	0.195	0.676	1.251

Table 8. Summary statistics across assessment models with different natural mortality priors. Columns 2-6 show the fits to important data components. 'PlusGroup' is the sum of the squared residuals of the plus group fit (age 31), and '% of base' is the percent of the sum of squares relative to Model 16.5.

Model #	Fishery Ages	Survey Ages	Fishery Size	Dom LL Survey Index	PlusGroup	%Change
16.5	239	219	41	30	0.032	100%
16.5r	242	221	40	30	0.033	103%
16.5s	239	219	41	30	0.032	100%
16.5t	239	220	41	30	0.032	100%

Table 9. Retrospective statistics for female spawning biomass across models with natural mortality assumptions. Mohn's ρ is the measure of bias in the estimates in the last 10 years, Wood's hole ρ is the bias in full the time series, RMSE is the root mean squared error of the spawning biomass over all years, and ϕ is the ratio of recent (Mohn's ρ) to historic (Wood's hole ρ) which indicates whether retrospective bias is higher recently rather than overall.

Model #	Mohn's ρ	Wood's Hole ρ	RMSE	ϕ
16.5	0.068	0.063	0.412	1.079
16.5r	-0.018	-0.004	0.491	4.500
16.5s	0.098	0.094	0.485	1.043
16.5t	-0.014	-0.095	0.506	0.147
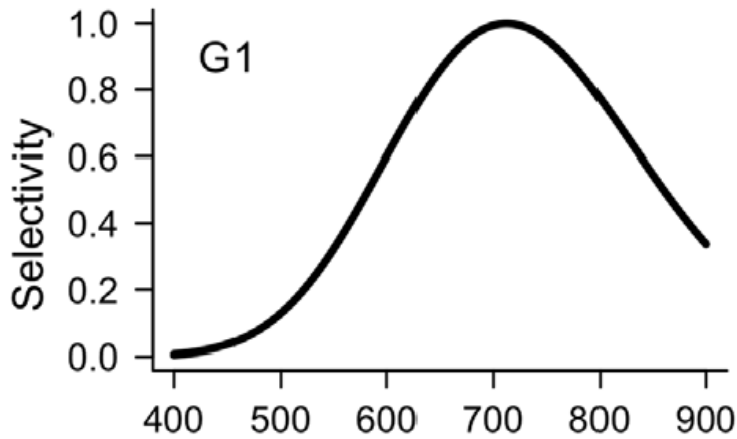
Figure 1. Size-selectivity (gamma, by length) for British Columbia Sablefish (Anoplopoma fimbria) estimated from a long-term tagging study. Source: Jones MK, Cox S. Fisheries Research. 2018 Mar 31;199:94-106.
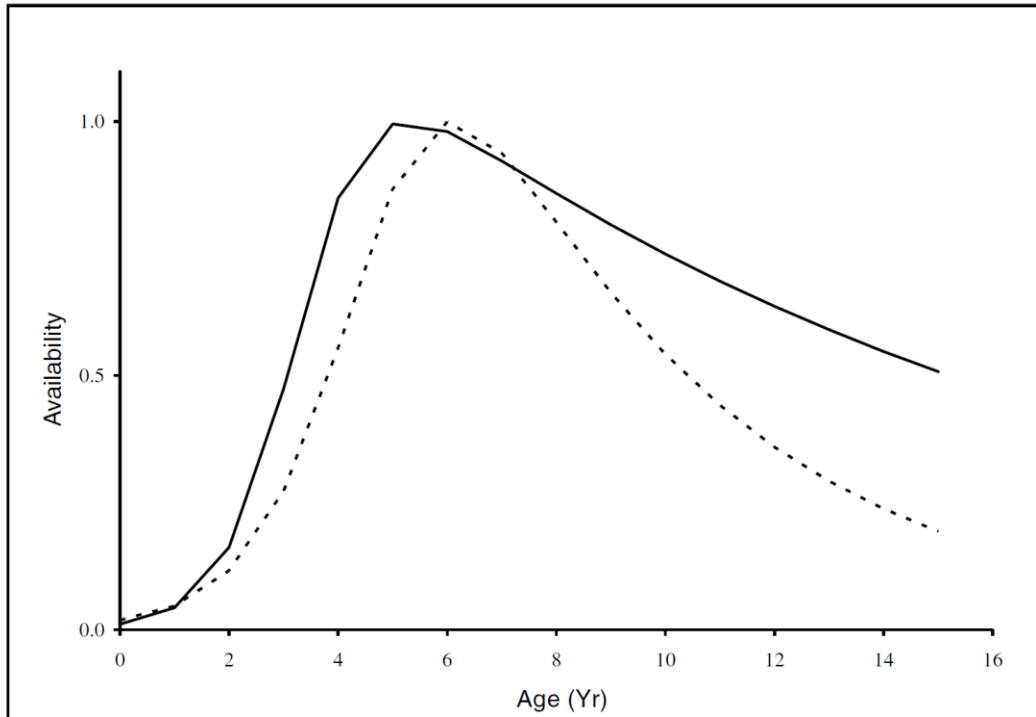
Figure 2. Estimated selectivity at age from tagging data for Alaska sablefish. Dashed line is IFQ (1995-2005), and solid line is from the derby fishery (1979 – 1994). Source: Maloney NE, Sigler MF. Age-specific movement patterns of sablefish (*Anoplopoma fimbria*) in Alaska. Fishery Bulletin. 2008;106(3):305-16.
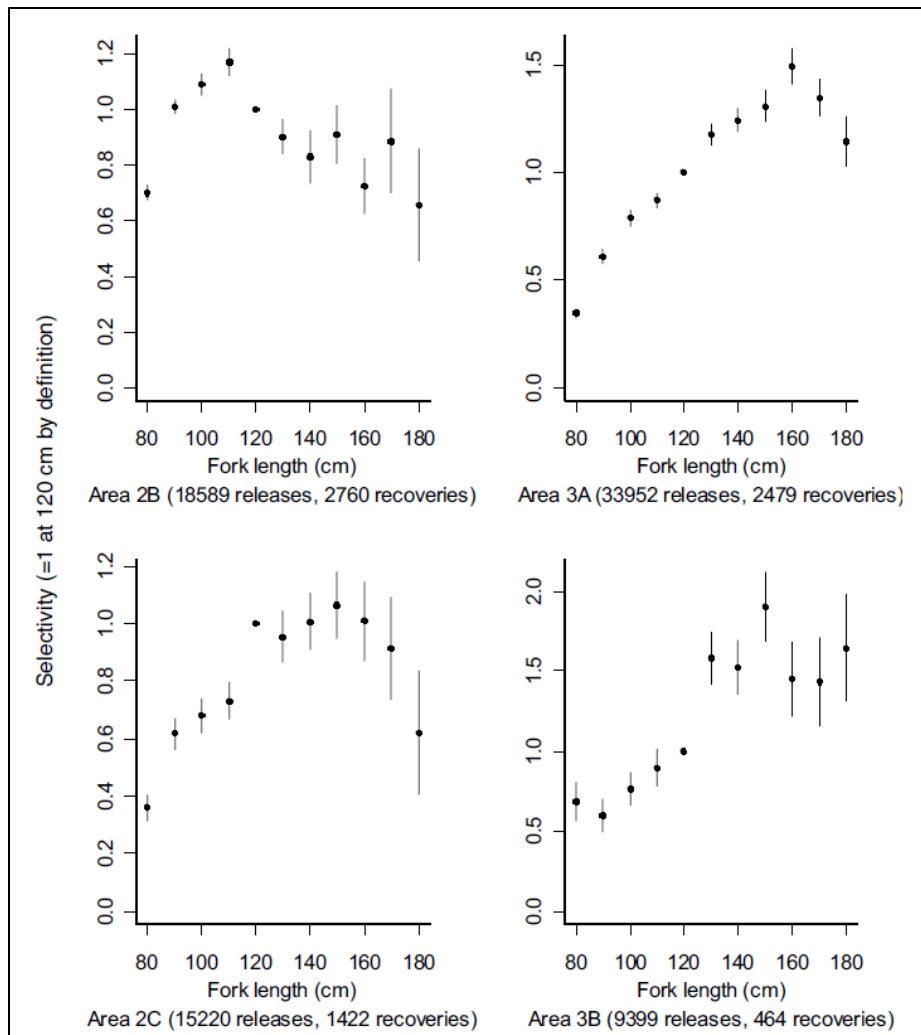
Figure 3. Estimates of length-specific selectivity for Pacific halibut by area from tag release data from 1960-1990. Source: Clark WG, Kaimmer SM. Estimates of commercial longline selectivity for Pacific halibut (*Hippoglossus stenolepis*) from multiple marking experiments. Fishery Bulletin. 2006;104(3):465-7.
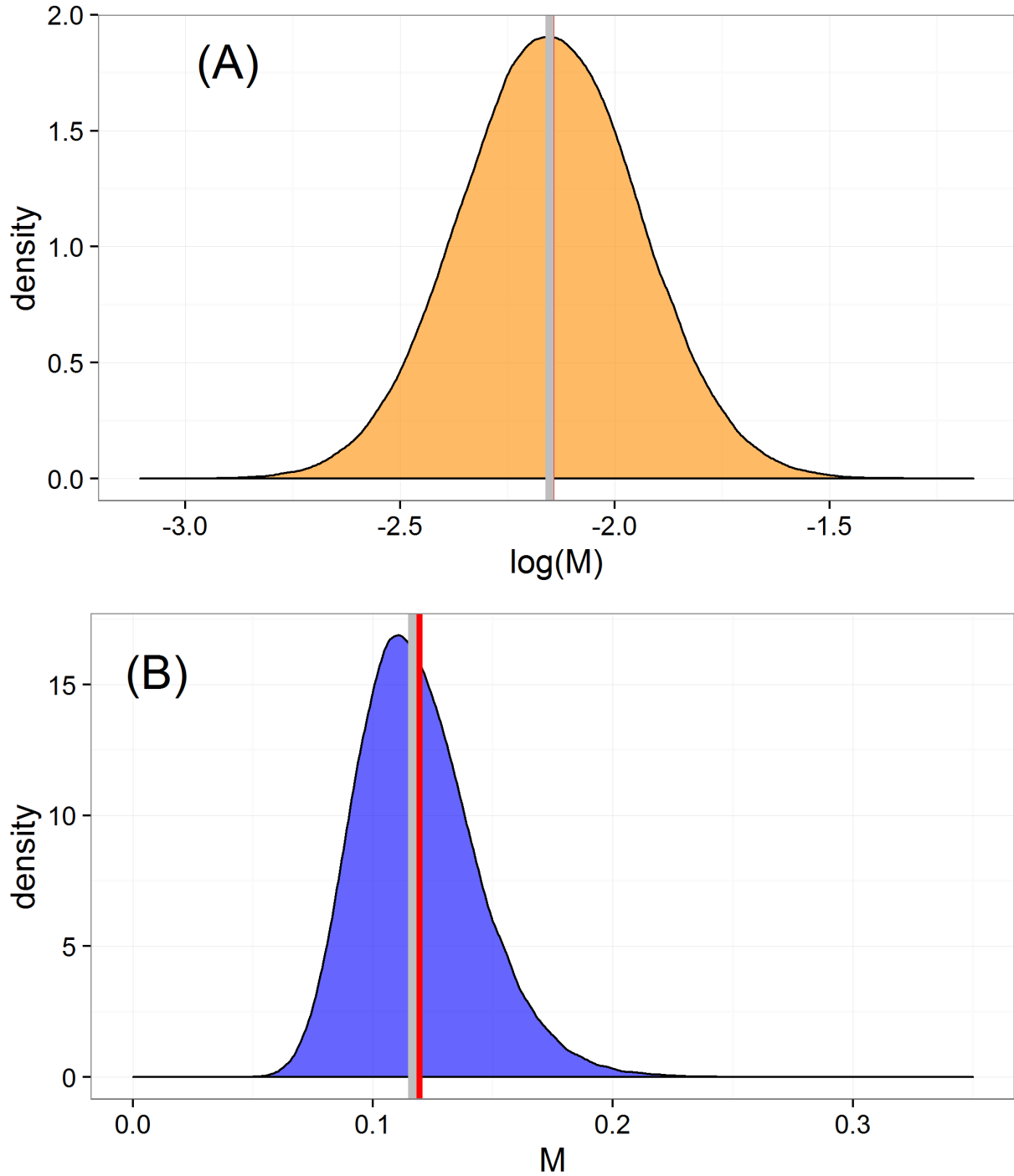
Figure 4. Lognormal prior distribution on log-scale (A) and natural scale (B) for natural mortality derived from multiple life history estimators and an independent mark-recapture estimate. The grey vertical line is the median and the red vertical line is the mean.
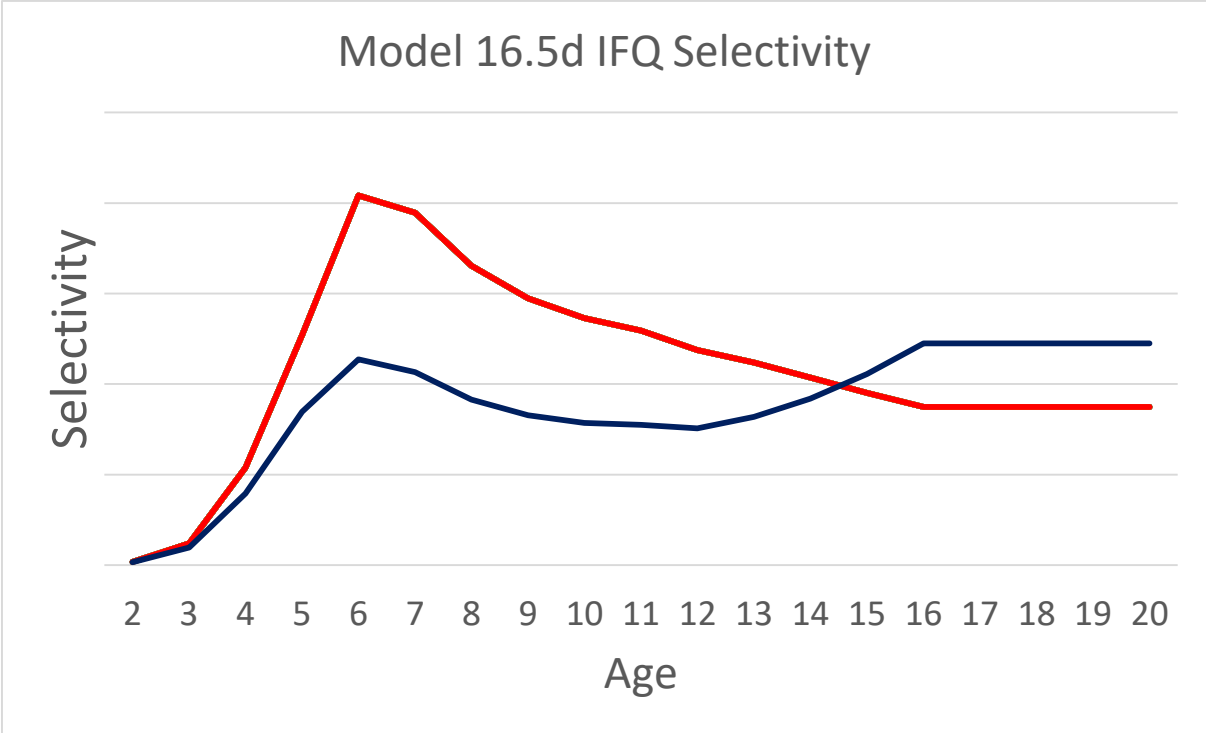
Figure 5. Female (red) and male (blue) selectivity for Model 16.5d with time-invariant non-parametric selectivity.
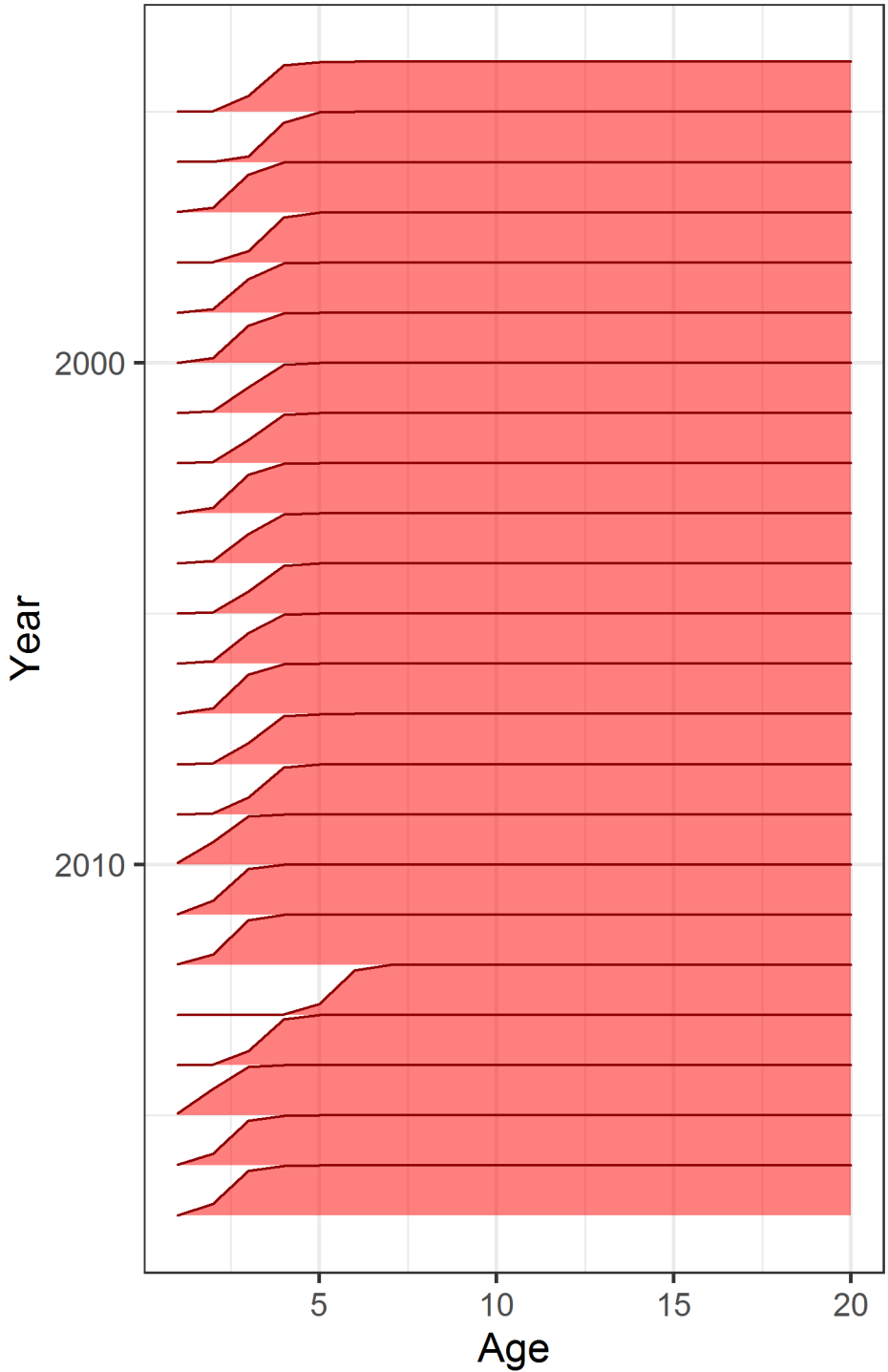
Figure 7. Female fishery selectivities for model 16.5i (time-varying logistic).
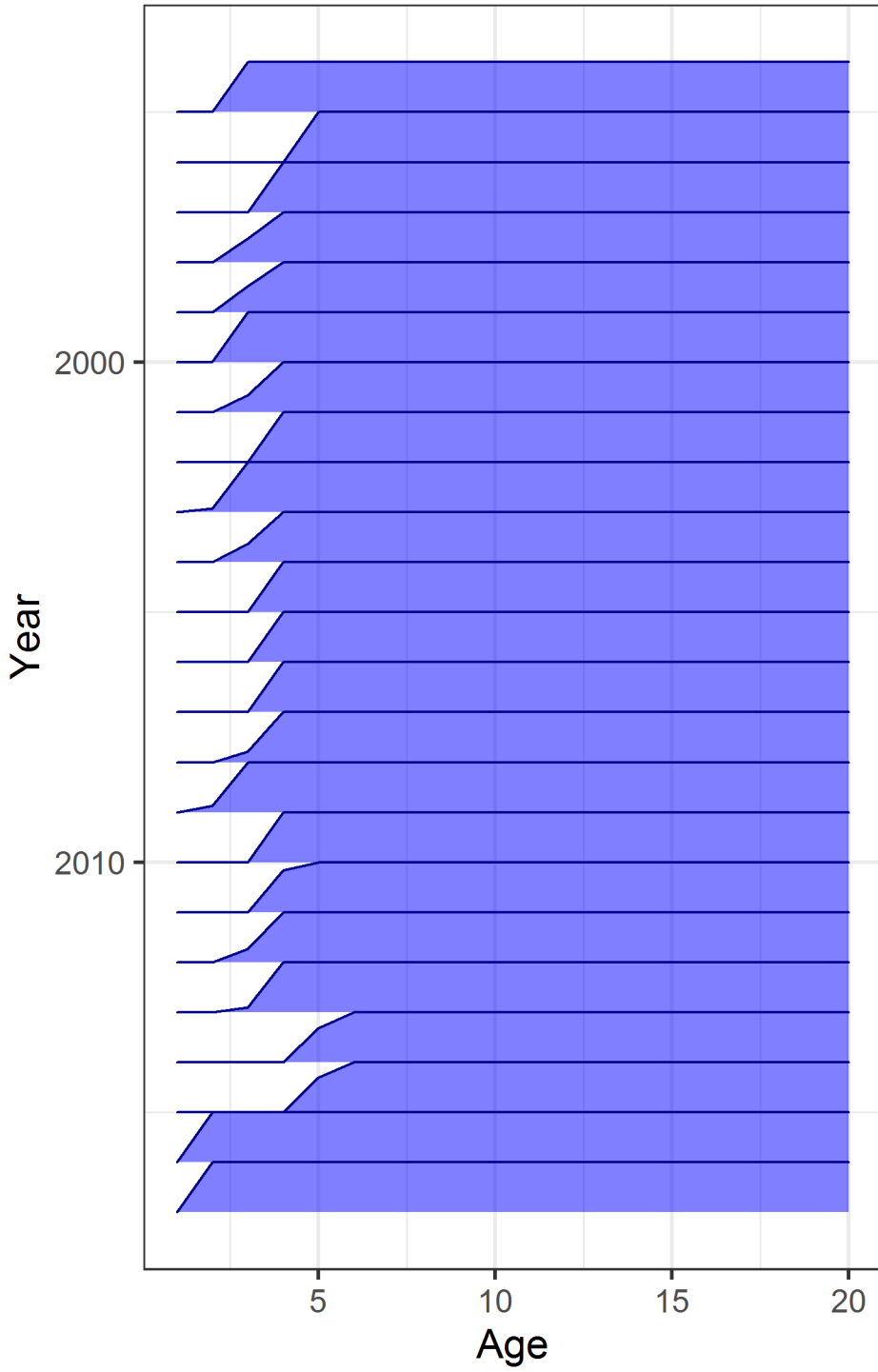
Figure 7. Male fishery selectivities for model 16.5i (time-varying logistic).
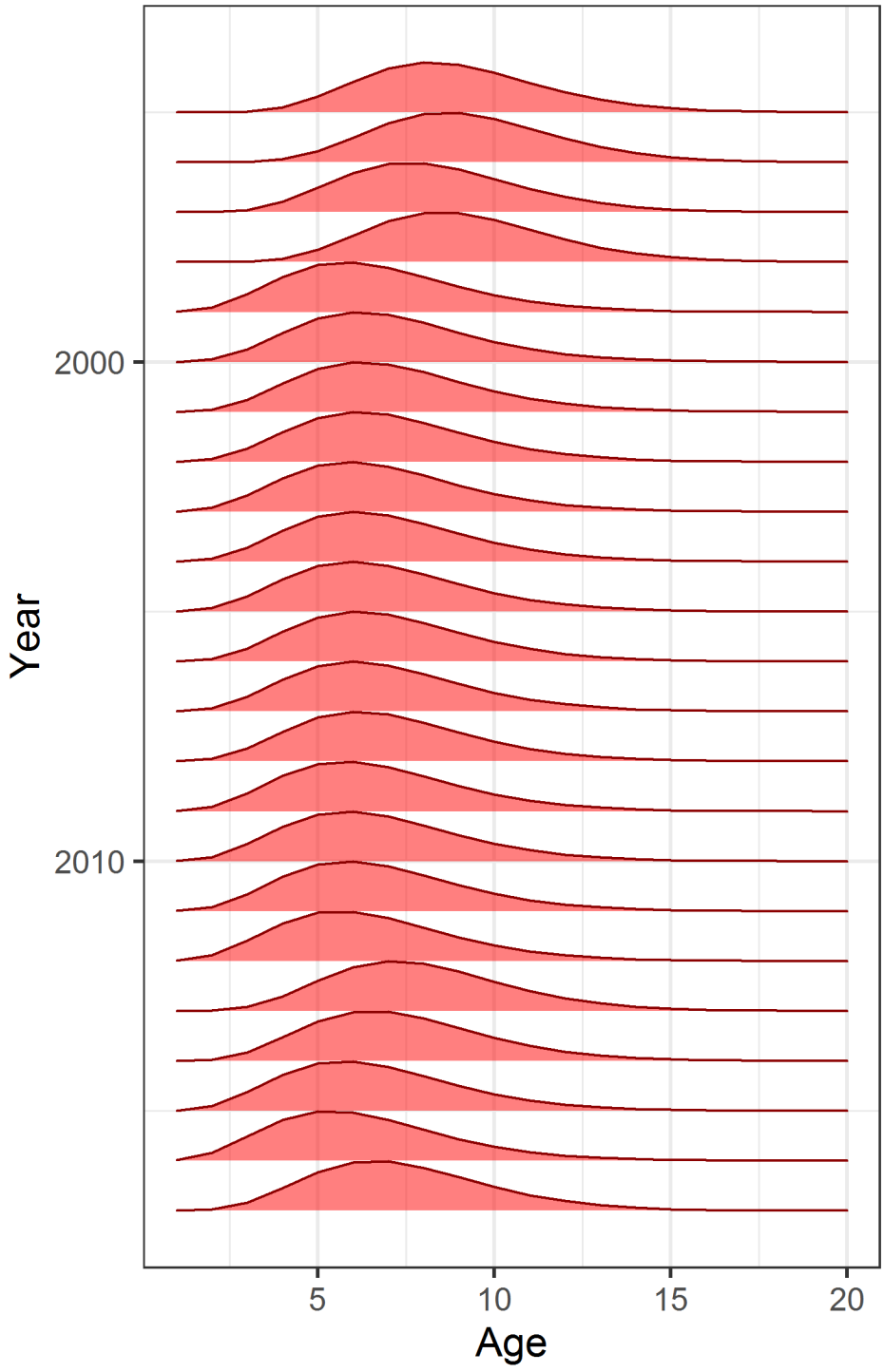
Figure 8. Female selectivity for Model 16.5j (time-varying gamma selectivity).
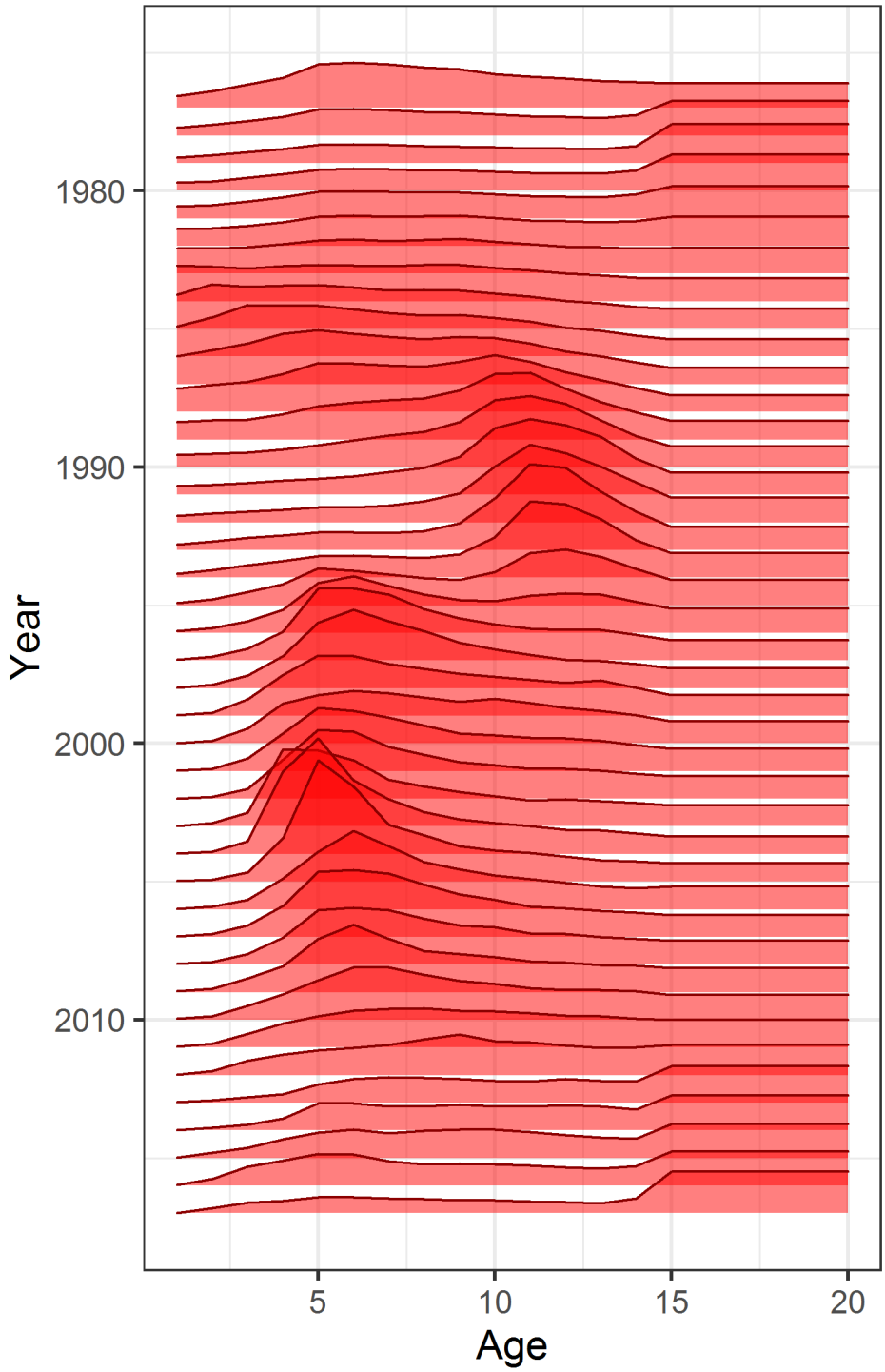
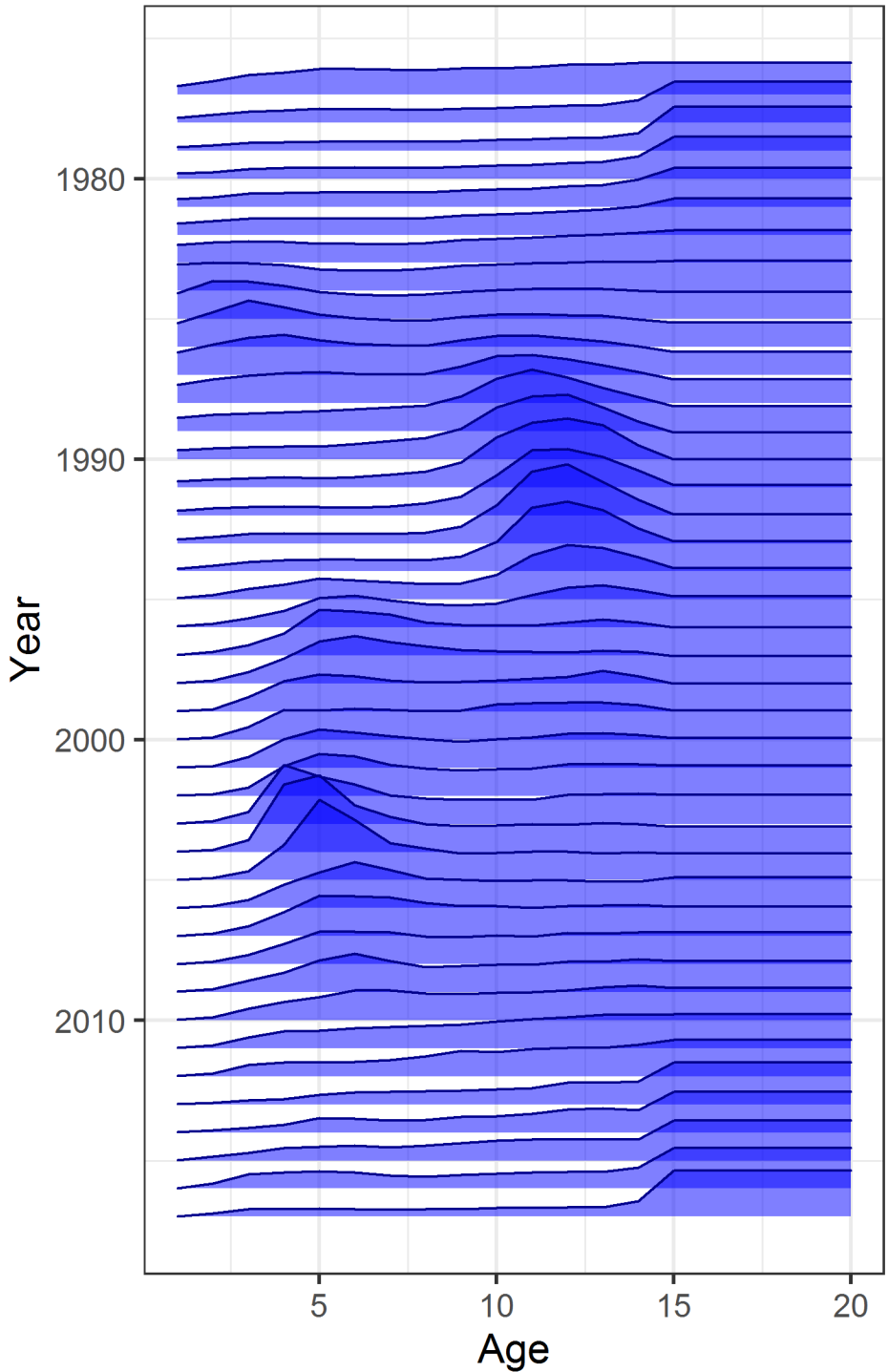Figure 9. Female fishery selectivities for model 16.5n (time-varying non-parametric selectivity).

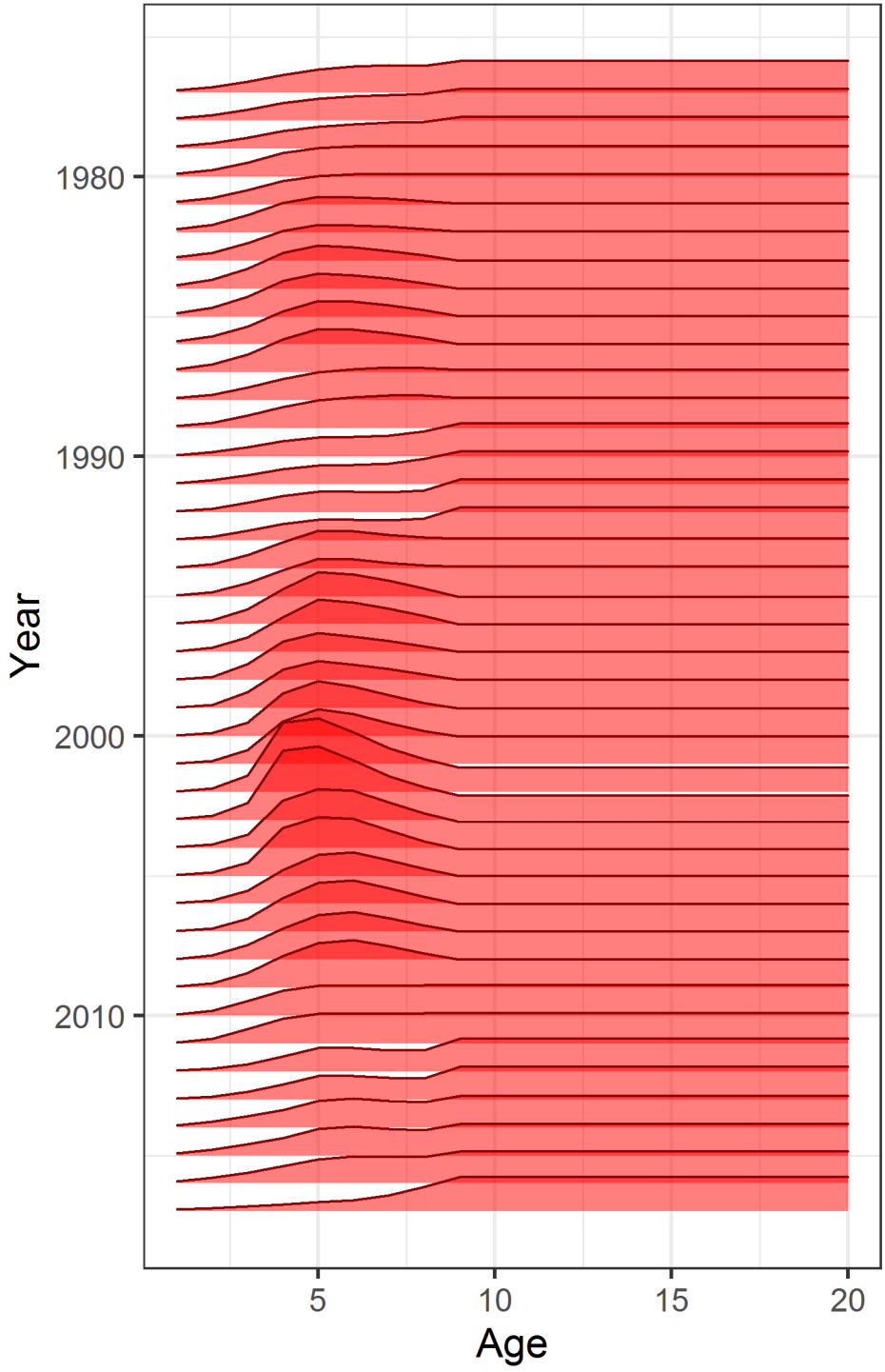Figure 10. Male fishery selectivities for model 16.5n (time-varying non-parametric selectivity).

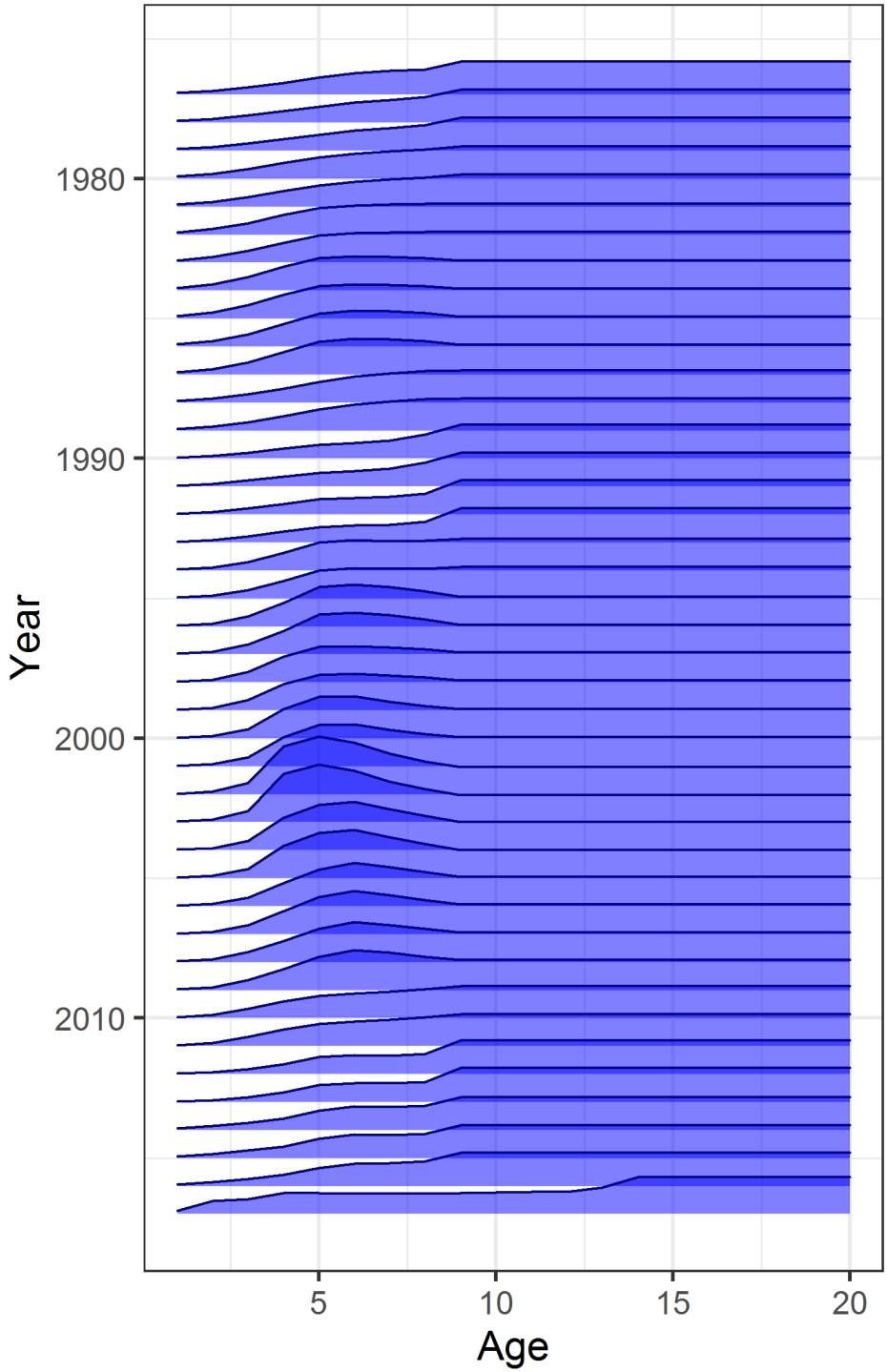Figure 11. Female fishery selectivities for model 16.5z (time-varying non-parametric with 2-year blocks).

Figure 12. Male fishery selectivities for model 16.5z (time-varying non-parametric with 2-year blocks).
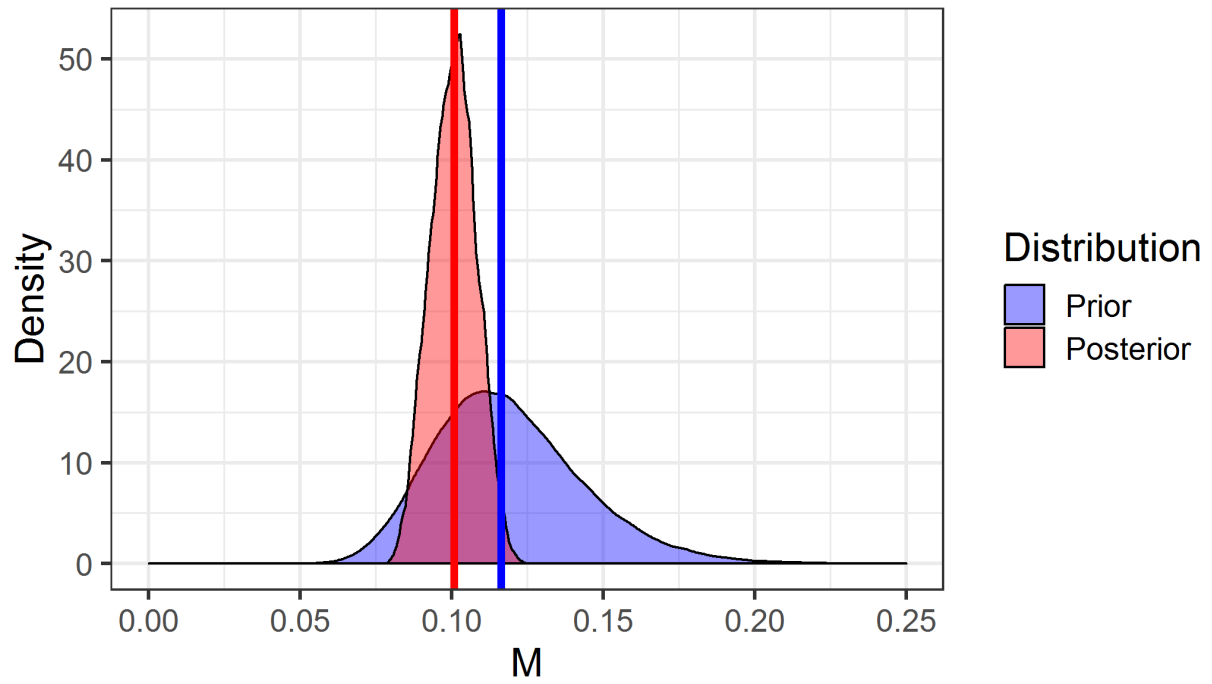
Figure 13. Prior (blue) and posterior (red) distributions of natural mortality for Model 16.5r which estimates natural mortality with the newly developed prior distribution.